*Computational Aeroacoustics: From Acoustic Sources Modeling to Far-Field Radiated Noise Prediction*
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# Understanding Slat Noise Sources

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**ABSTRACT**

*Model-scale aeroacoustic tests of large civil transports point to the leading-edge slat as a dominant high-lift noise source in the low- to mid-frequencies during aircraft approach and landing. Using generic multi-element high-lift models, complementary experimental and numerical tests were carefully planned and executed at NASA in order to isolate slat noise sources and the underlying noise generation mechanisms. In this paper, a brief overview of the supporting computational effort undertaken at NASA Langley Research Center, is provided. Both tonal and broadband aspects of slat noise are discussed. Recent gains in predicting a slat's far-field acoustic noise, current shortcomings of numerical simulations, and other remaining open issues, are presented. Finally, an example of the ever-expanding role of computational simulations in noise reduction studies also is given.*

## INTRODUCTION

Projected growth in air travel and significant quieting of modern jet engines has brought renewed attention to the nonpropulsive (airframe) component of aircraft noise. Past studies that focused on airframe noise identified high-lift devices and landing gears as dominant noise producing components [1,2]. NASA, in collaboration with industrial and academic partners, has embarked on a major research program to enhance our fundamental understanding of airframe noise sources and to apply this knowledge to noise reduction technologies that are both effective and aerodynamically efficient.

NASA Langley Research Center's (LaRC) overall strategy for isolating relevant airframe noise sources consists of several building block steps that include:

1. constructing simplified model configurations that allow detailed aeroacoustic measurements and computations of a desired airframe component to be performed,
2. using microphone array measurements to reveal acoustic hotspots and far-field spectra and directivity,
3. conducting steady Reynolds-averaged Navier-Stokes (RANS) computations to highlight the near-field flow phenomena that could either produce or support flow unsteadiness,
4. performing finely resolved unsteady RANS (URANS) computations to capture the time-dependent flow field of a suspect flow phenomenon identified in step 3,
5. using the computed near-field unsteady flow field as input to an acoustic analogy formulation to compute the far-field acoustic noise.

In this paper, we present an overview of the major noise generation mechanisms associated with a leading-edge slat with a focus on the important role of computational simulations in identification and understanding of noise sources underlying the experimentally measured noise spectra. Due to space constraints, discussion will be limited to those results that were obtained during steps 4 and 5 of the above plan.

To isolate the characteristics of slat noise, researchers at NASA conducted tailored aeroacoustic tests of generic high-lift configurations [3,4,5]. These particular experiments, along with the studies conducted in Europe by Dobrzynski et al. [6], revealed that slat noise by itself is a complex aeroacoustic problem that involves a combination of interdependent noise generation mechanisms in overlapping frequency bands. Based on the microphone array and acoustic mirror measurements obtained in these tests, a generic picture of the slat frequency spectrum has emerged.

Fig. 1 shows a typical slat frequency spectrum for landing approach conditions. The measurements show high sound levels in the lower frequency range followed by a gradual drop in the levels as the mid-frequency range is approached. At higher frequencies, the spectrum displays a broadband tonal behaviour and a concurrent rise in the acoustic intensity. The peak is significantly higher than the noise for the surrounding frequencies. In fact, for certain test conditions, the sound levels associated with this tonal noise were so high that they virtually masked other sources of noise [5].

## NUMERICAL SIMULATIONS

The shape of the spectrum and the disparity between the frequencies of the two major features revealed the presence of two dominant noise sources. The scale disparity also demanded that the simulations be tailored to achieve a certain level of spatial resolution for the local regions of the flow where the relevant noise generation mechanism was deemed to be active.

### High frequency source

The initial set of URANS computations focused on the high frequency slat noise source. The simulations were designed to test the conjecture that vortex shedding at the slat trailing edge was the likely source for producing high frequency noise. To investigate the vortex shedding conjecture, URANS computations of an energy efficient transport (EET) wing were performed [7]. For these simulations, the treatment of the trailing-edge bluntness was a crucial and important step. To accurately predict the slat's vortex shedding, the computational trailing-edge geometry matched the actual thickness (0.5 mm) rather than being idealized as a sharp edge. In addition, an extremely fine grid with significant mesh clustering was employed at the trailing edge.

A sample instantaneous spanwise vorticity field at the trailing edge [7] is plotted in Fig. 2. The established vortex street is clearly displayed and confirms the conjectured vortex shedding at the trailing edge. Because of coarsening grid resolution beyond two vortex diameters downstream of the trailing edge, the convected vortices decay rapidly farther downstream. Analysis of the unsteady pressure field revealed a purely periodic signal in the vicinity of the edge. The highest amplitude pressure fluctuations occur at the two sharp corners of the edge. The computed tonal frequency was found to be within the range of the experimentally measured frequencies for the hump in the spectrum. The propagating waves and the established wave patterns near the slat trailing edge and cove areas are shown in Fig. 3. Of particular significance is the reflection of the wave at the leading edge of the main element, which results in a distinct interference pattern across the gap and in the cove area.

Using an acoustic analogy formulation (the Ffowcs Williams and Hawkings equation), Singer et al. [8] computed the far-field acoustics from the time records of the URANS computations. Overall, the agreement between the computed far-field acoustics and the array measurements supports the conclusion that the simulated near-field flow dynamics was reasonably accurate. Follow-on experimental studies [4, 9–12] have firmly established the presence of vortex shedding at the slat trailing edge. Theoretical work pertaining to the role of slat gap resonance in explaining the high-intensity spectral hump at large frequencies has been pursued by Tam and Pastouchenko [13] and Agarwal and Morris [14].

### Low frequency source

The next series of URANS simulations [15] tested the conjecture that amplified perturbations in the free shear layer are responsible for the low frequency content of the slat acoustic spectra. Similar to the trailing-edge noise studies, the computational framework of URANS plus the Ffowcs Williams and Hawkings formulation was followed to calculate the far-field acoustics.

The initial fully turbulent simulations of ref. [15] required explicit forcing of the shear layer to excite and maintain the large-scale structures. However, these computations proved to be overly diffusive; the rolled-up vortices rapidly decayed within a short spatial distance. This premature diffusion prevented proper development of the cove flow field, inhibited the passage of vortices through the gap between the slat and the main element, and artificially decreased the intensity of far-field noise. Although better agreement with experimental measurements remained desirable, the computations reinforced the speculation that interaction of shear layer instabilities with nearby solid surfaces can account for significant noise production in the lower frequency range.

To circumvent the excessive diffusive effects of the turbulence model, a simple zonal approach based on physical arguments was advocated and pursued [16,17]. In the cove region, the established flow field is quasi-laminar but highly unsteady. Accordingly, the production term associated with the turbulence model was switched off in a limited zone that enclosed the cove area. A sample plot of the instantaneous spanwise vorticity field from the partially laminar simulation at an angle of attack of 6° is shown in Fig. 4. In contrast to the fully turbulent simulations, the cove region displays extremely complex and highly nonlinear flow dynamics. Important stages, such as shear layer oscillation, roll-up, and the formation of discrete vortices, are vividly depicted. Furthermore, unlike the fully turbulent case, the shear layer is self-exciting and no external forcing was necessary. The figure also clearly shows the ejection of several vortices through the gap region. The ejected vorticity field is spread over a significant portion of the gap width. These observations corroborate the particle image velocimetry (PIV) measurements obtained at angles of attack of 4° and 5° by Paschal et al. [18] and Takeda et al. [19]. However, rather intense near-field fluctuations in the simulated flow were found to be associated with unsteady separation along the slat bottom surface, relatively close to the slat cusp. The accuracy of the laminar-cove simulations in this near-wall region is an open issue. Another open issue is the presence of a very large and strong vortex of positive vorticity near the center of the recirculating zone. The center vortex produces low frequency oscillations. The existence of such a prominent vortex has not been observed in the limited PIV data available. The low frequency oscillations may be acoustically irrelevant in a full-scale environment; nevertheless, the presence of the center vortex greatly alters the dynamics of the cove flow field and thus requires further exploration.

Unsteady flow data were used as input for the solution of Ffowcs Williams and Hawkings equation to calculate the noise radiated below the high-lift system. A sample of the computed and measured acoustic spectra at an angle of attack of 6° [16] is displayed in Fig. 5. The shape of the spectrum over the entire frequency band (including the shedding frequency) is well captured. The decay with frequency is similar for the computation and experiment. The higher acoustic amplitude in the predicted spectrum is due to the perfect spanwise correlation assumed for the near field unsteady signal. In an actual experiment, three-dimensional effects provide a spanwise correlation that is less than perfect. Therefore, a two-dimensional acoustic computation potentially overestimates the noise significantly. The magnitude of this overestimation is an open question that needs to be resolved with expensive three-dimensional simulations. Such studies are ongoing at NASA LaRC and in Europe [20].

**Noise reduction study**

More and more, in noise reduction proof-of-concept studies, computational simulations are being used as a cost-effective alternative to expensive experimentation. An example is provided below.

To diminish the potent pressure fluctuations at the slat trailing edge (due to vortex shedding), several techniques are available. The effectiveness of one treatment, advocated in ref. [21], was demonstrated through URANS simulations of the unsteady flow past the EET high-lift configuration. The approach applies a passive porous treatment to a small select surface area of a slat trailing-edge region (a similar idea was employed by Dobrzynski et al. [6]). The porous edge provides a mechanism for flow communication among the slat lower, end, and upper surfaces, and therefore allows a modified lift distribution to be established at the trailing edge. The computational simulations showed that the peak pressure fluctuations near the trailing edge were reduced by an order of magnitude after the edge treatment had been turned on [21]. A comparison of the mid-field pressure contours between the untreated and treated cases indicated that the far-field noise is likely to be reduced by more than 20 dB.

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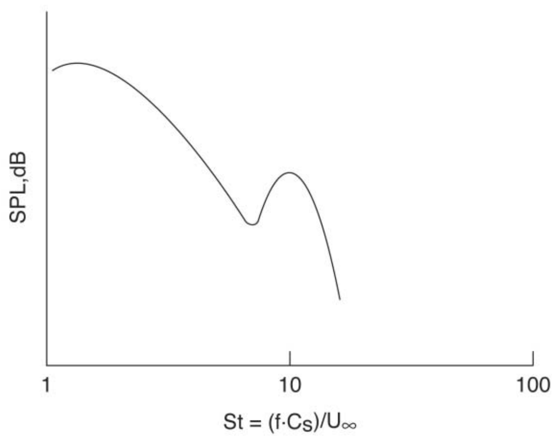


***Figure 1:*** *Typical slat frequency spectrum. Cs represents slat chord.*

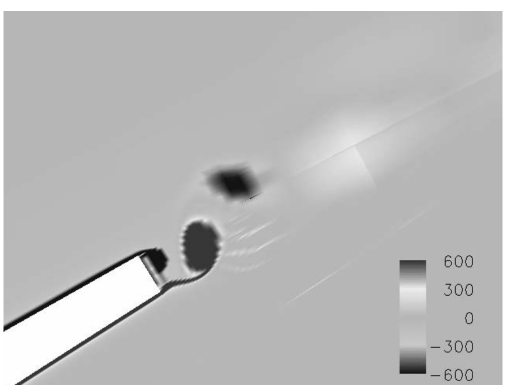


***Figure 2:*** *Instantaneous spanwise vorticity field at slat trailing edge.*

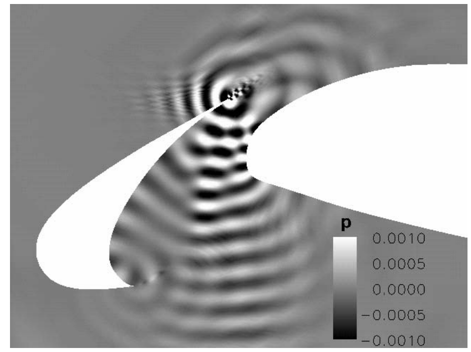


***Figure 3:*** *Instantaneous fluctuating pressure field.*

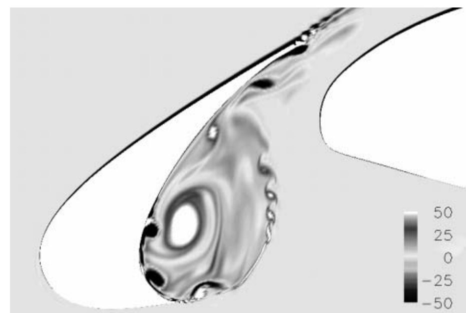


***Figure 4:*** *Instantaneous spanwise vorticity field for partially laminar simulation of cove.*

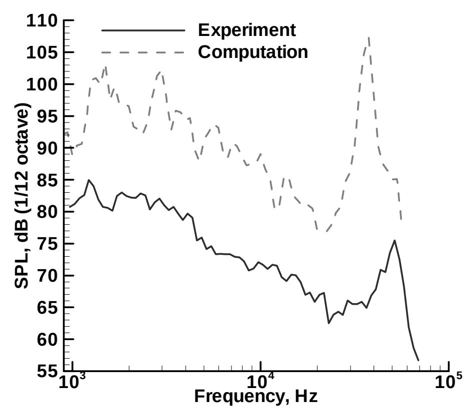


***Figure 5:*** *Measured and computed acoustic spectra for slat in 1/12–octave bands. Frequencies are model scale.*